A Microwave Heating Demonstrator (MHD) payload concept for lunar construction and volatiles extraction

Conference or Workshop Item

A MICROWAVE HEATING DEMONSTRATOR (MHD) PAYLOAD CONCEPT FOR LUNAR CONSTRUCTION AND VOLATILE EXTRACTION. S. Lim[1] (sungwoo.lim@open.ac.uk), S. Reeve[2], A. D. Morse[1], A. Garbayo[2], J. Bowen[3], and M. Anand[1,4], [1]School of Physical Sciences, The Open University, Milton Keynes, MK7 6AA, [2]Added Value Solutions UK Ltd., [3]School of Engineering and Innovation, The Open University, Milton Keynes, MK7 6AA, [4]Department of Earth Sciences, The Natural History Museum, London, UK.

Introduction: A sustainable and affordable exploration of the Solar System cannot rely solely on Earth's resources and must use materials obtained and processed *in situ*. The current Solar System exploration road map, put together by a consortium of international space agencies envisage a longer-term presence on the Moon by 2028. Thus, the development of *In-Situ* Resource Utilisation (ISRU) to offset the need to transport all materials from the Earth is essential and timely. Based on our expertise in lunar science and building space instrumentation at the Open University, and by working in partnership with our industrial partners, we have established a consortium to develop a microwave heating-based 3D printing technique as a fabrication method for extra-terrestrial construction process and resource extraction, including oxygen, water and metal (e.g. iron). Alignment of our proposed work with the Global Exploration Roadmap (GER) is shown in Figure 1.

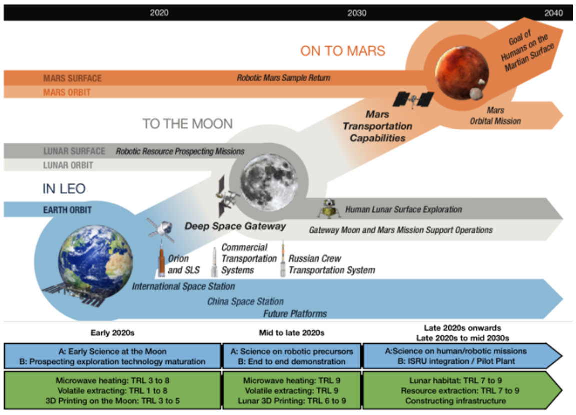
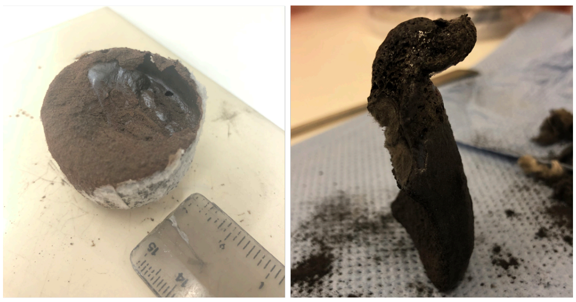


Fig 1: Alignment of our proposed research on lunar construction and ISRU activities (green) with GER and ESA's ISRU mission roadmap (blue boxes).

For an extended stay on the Moon, humans will require habitation with substantial shielding for protection from radiation and micrometeorites. Lunar regolith (soil) is a readily available *in-situ* resource, which can be thermally treated to extract oxygen and water, as well as for construction. For example, lunar habitats and infrastructure can be built by robots using additive manufacturing techniques [1]. Due to the volumetric heating characteristic, intrinsic to microwave heating, it is a more energy-efficient process than solar or laser sintering for large-scale manufacturing and construction purposes. Proof of concept experiments [2-4] have demonstrated that microwaves couple efficiently with lunar regolith simulants; therefore, microwaves could be an efficient mechanism to sinter and melt lunar regolith to build 3D structures, and also enable the extraction of volatiles.

These experiments are based on simulated conditions and materials; thus, there is missing information on microwave heating of lunar regolith, which includes the effects of nanophase iron (np-Fe^0) produced via space weathering, the highly electrostatic nature of the particles, and irregular particle geometries of the real lunar soil. Through a UK Space Agency (UKSA) grant (NSTP GEI) we are developing a conceptual design of the Microwave Heating Demonstrator (MHD) payload that could be delivered to the lunar surface for *in-situ* experiments via the ESA's HERACLES mission or NASA's CLPS programme. Here, we provide further details of our conceptual design of a MHD payload.

Microwave heating of lunar regolith: Our simulation [2] and lab experiments [3,4] have demonstrated that lunar regolith (highlands and mare) and simulant JSC-1A can be sintered and melted using as low as ~200-250 W input power under ambient atmospheric conditions while experiencing severe thermal runaway. It was found that (i) microwave energy couples well with both highlands and mare lunar regolith (numerical modelling) and their simulants JSC-1A (numerical modelling and experiments), and (ii) the temperature threshold of thermal runaway exists between 600 and 700 °C depending on the phase transition of the material. Further, through lab experiments under various input powers, it was confirmed that temperature (but not input power) is the main criterion for thermal runaway in microwave heating.



(a) (b)

Fig 2: Microwave heated JSC-1A under (a) ambient pressure, and (b) low-pressure ($4.6e^{-5}$ hPa).

In the context of a MHD operating at the lunar surface, it is important to investigate the microwave heating behaviour of lunar material under reduced pressues. In this respect, our preliminary lab experiment involving microwave heating of lunar simulant JSC-1A under lower-pressure generated plasma due to the ionized volatiles, and a highly porous molten specimen, resulting in a lower yield rate of the sintered and melted specimen (13 g out of 50 g) than that of the specimen treated under a standard ambient pressure (50 g out of 50 g) as shown in Fig 2. Somewhat speculative, but possible, reasons include (i) less microwave energy absorption due to the plasma formation, and (ii) severe porosity of the specimen due to the rapid release of volatiles which possibly restricts the spread of the hotspot region due to poorer heat transfer through the porous regions.

Microwave Heating Demonstrator (MHD): In order to design the MHD, the payload requirements were first reviewed. These included the available power, interface, and mass/volume of the payload, from a potential lunar ISRU lander. Pre-defined computational simulations using COMSOL Multiphysics software were also conducted to determine the optimal input power, heating time, specimen mass and crucible shape for the experiment, which maximises the energy absorption while minimising the total energy input between room temperature and melting point. Then, a sequential operation of each experiment was carefully planned, followed by developing a conceptual hardware design for the MHD payload based on the functional diagram of MHD (Fig. 3). The MHD payload consists of a solid-state microwave generator, bespoke cavity, mass spectrometer, pyrometer, data logger, telemetry and crucible delivery unit with an optional material collection unit.

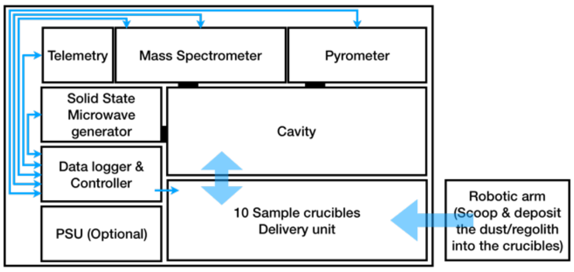


Fig 3: Functional diagram of MHD

The main functions of MHD and the sequence of experiment are to (i) collect up to ten lunar regolith samples (50 g each) depending on the lander mission and the lander path/destination, (ii) heat each specimen with 250 W of input power for up to 60 minutes, and (iii) measure the temperature of the specimen and released volatile profiles every second. The measurement of the specimen temperature is continued until it is cooled down to ambient temperature. More specific functions and a 3D CAD model of a MHD conceptual design of MHD will be presented at the meeting.

The MHD payload will produce scientifically invaluable findings in their own right. The outcomes of the experiments would also fill the knowledge gaps in Space Science and Engineering disciplines by revealing the physicochemical characteristics of thermally treated lunar regolith using microwave energy under the real lunar environment. It will provide useful insight into the properties of materials which have been thermally treated material properties by microwave energy on the Moon and potential opportunities on other airless bodies with near-vacuum atmospheres, e.g. Martian moons and asteroids, which are of interest to exploration communities worldwide. Ultimately, our research will lead us to realise lunar construction and ISRU mission activities, as indicated in Figure 1.

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References: [1] Lim, S. et al. (2017) *Adv. in Space Research J.*, 60(7), 1413-1429. [2] Lim S. and Anand M. (2019) *Special Issue on Space Resources, Planet. and Space Sci J.,* 179(104723). [3] Lim S. et al. (2019) *Lunar ISRU2019*, Abstract #5047. [4] Lim, S. et al. (2019) *ELS2019,* Session 6: Prospecting and ISRU.